TECHNICAL REPORT

67-54-GP

GUIDE FOR ESTIMATING MAXIMUM ANCHOR LOADS ON AIR-SUPPORTED STRUCTURES

by

Thomas C. Strain

and

Ronald F. Tumeinski

March 1967

UNITED STATES ARMY
NATICK LABORATORIES
Natick, Massachusetts 01760

General Equipment & Packaging Laboratory

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GUIDE FOR ESTIMATING MAXIMUM ANCHOR LOADS ON AIR-SUPPORTED STRUCTURES

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Thomas C. Strain
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Project No. 1M642101D503

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FOREWORD

This report was prepared by the Shelters Division, General Equipment and Packaging Laboratory, U. S. Army Natick Laboratories, Natick, Mass. The work was performed under Exploratory Development Project 1M642101D503, "Tents and Organization Field Equipment," Task 01, Studies in the Structural Mechanics of Tentage, Work Unit 003, Review of Design Manual.

Its contents are based on the technical data contained in the "Design Manual For Ground-Mounted, Air-Supported Structures," prepared by the Hayes International Corp. Birmingham, Alabama, for NLabs under contract DA19-129-AMC-129.

The intent of this report is to provide the design engineer with a complete, concise guide for planning the ground support and anchoring devices required for stabilizing air-supported structures.

The authors wish to acknowledge the guidance, encouragement and support of Mr. C. J. Monego of the Shelters Division in the preparation of this work.

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SYMBOLS

A_f	Floor area, sq ft
A_p	Planform area (max. horizontal cross sectional area), sq ft
AL	Anchor Load, lbs
AL_e	Anchor load due to internal pressure, lbs
BL	Base anchor load, lbs
C_{AL}	Anchor load coefficient, single-wall
C_{BL}	Base anchor load coefficient, double-wall
C_{GL}	Guyline anchor load coefficient, double-wall
d	Reference length - tent diameter, ft
GL	Guyline anchor load, lb
h	Tent height, ft
l_t	Length of tent, ft
P_{AL}	Total anchor load, lbs
P_e	Shelter enclosure pressure, lb/sq ft
q	Dynamic (impact) pressure, lb/sq ft
r	Tent radius, ft
U	Velocity, ft/sec
W	Tent width, ft
ρ	Density of air, Slugs/cu ft

ABSTRACT

This report contains all the graphs, tables, mathematical formulas, and design data necessary to estimate the maximum loads on anchoring systems used with air-supported shelters subjected to winds up to 105 mph. The design data are presented in non-dimension coefficient form. Sample problems are included to illustrate the use of the data and their application to both single and double-wall structures.

GUIDE FOR ESTIMATING MAXIMUM ANCHOR LOADS
ON AIR-SUPPORTED STRUCTURES

1. Introduction

In October 1950, a Design Manual for Spherical Air-Supported Radomes was published as Cornell Aeronautical Laboratory Report No.UB-664-D-1. After its publication, the radome was adopted as standard by the military on many ground-mounted radar installations. Hundreds were built and considerable experience with their design and operations had been gained in the field.

In March 1956, the Cornell Design Manual was revised to incorporate information accumulated since its original publication. This revised manual, is designated as: "Design Manual for Spherical Air-Supported Radomes (Revised) Report No. UB-909-D-2."

Air-supported shelters were being developed for the military, varying in shape from spherical radomes to cylindrical structures with spherical or flat ends. Although the spherically shaped radome had been subjected to aerodynamic testing, no studies were made for other shapes. The design of other configurations was based on fragmentary information available from various sources. The need for reliable design information was obvious.

To obtain aerodynamic data on flexible, cylindrical, air-supported structures, a limited wind tunnel study was conducted at the Massachusetts Institute of Technology on a one-tenth scale model of the Army's standard, tent, air-supported, single-wall, nike-hercules, above-ground launcher. As a result, a final report was prepared by Raffi J. Bicknell entitled, "Wind Tunnel Test on an Air-Supported Tent Model" Report No. 1024, Department of Aeronautics and Astronautics, Wright Brothers Wind Tunnel, MIT, June 1963.

Beginning in July 1963, the U.S. Army Natick Laboratories contracted a program with the Hayes International Corp. for extensive wind tunnel studies on spherical and cylindrical <u>single-wall*</u> structures and cylindrical <u>double-wall**</u> structures.

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*<u>Single-Wall</u> - A flexible structure consisting of a single membrane usually in the shape of a sphere or cylinder. It is supported by a continuous flow of high volume, low pressure air enclosed between the membrane and mounting surface.
**<u>Double-Wall</u> - A flexible structure consisting of two membranes usually in the shape of a half cylinder. The two membranes form an envelope containing air, which resembles an air mattress bent into a "U" shape. The structure is supported by a flow of low volume, high-pressure air.

This program consisted of analytical and wind tunnel stdies on 26 scale model air-supported structures. This contract resulted in a design manual entitled, "Design Manual for Ground-Mounted Air-Supported Structures." It provides design criteria to facilitate engineering of aerodynamically stable air-supported structures. Included in the design manual are data for estimating maximum anchor loads to be expected in winds up to 105mph. The contents of the present report are based on the data contained in the Hayes report. It is prepared for the convenience of engineers whose primary interest is the anchoring of military shelters.

2. Anchor Load Calculations

a. Forces Creating Anchor Loads

Fabric shelters subjected to winds of high velocity can experience aerodynamic forces of considerable magnitude. In order to estimate the magnitude of these forces, twenty six single and double-wall shelter models were tested in a wind tunnel with winds up to 105 miles per hour. The aerodynamic force data obtained, were reduced to non-dimensional coefficient form by dividing the force data by a reference area and the dynamic pressure.

Several very important facts should be emphasized at this time. The aerodynamic force data used here were maximum values so that the anchor loads calculated by techniques in this report will be maximum loads. The second fact is that no attempt has been made to ascertain the effect of wind gusts. The impact pressure used is for a wind of constant velocity.

The tent planform area A_p was selected as the reference area and is defined as the maximum cross sectional area in a horizontal plane. Planform areas are given by the following expressions for common tent types:

Sphere

$$A_p = \pi \left(\frac{W}{2}\right)^2$$

Cylinder with spherical ends:

$$A_p = \pi \left(\frac{W}{2}\right)^2 - W(1 \underset{h}{-} W)$$

Figures 1 through 3 are examples of air-supported structures.

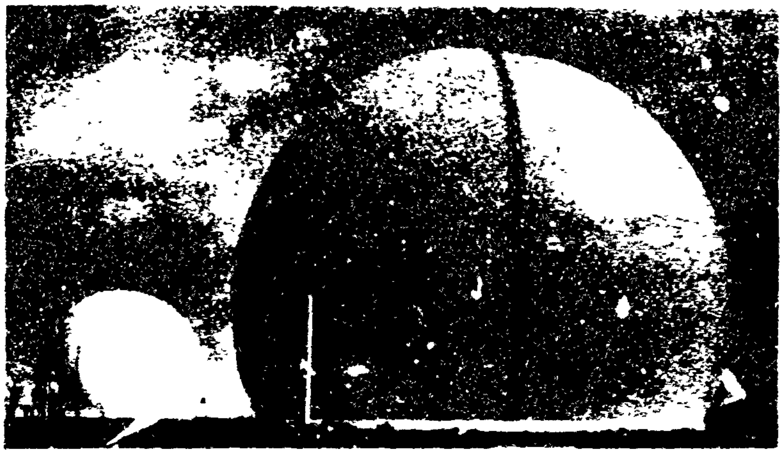

Figure 1. Single-Wall, Spherical

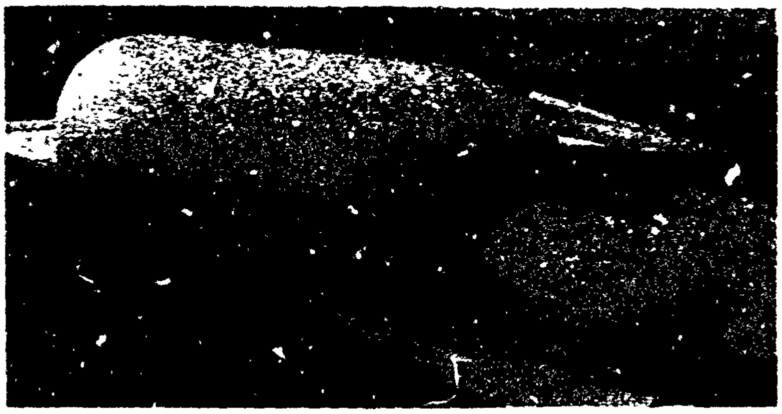

Figure 2. Single-Wall, Cylindrical

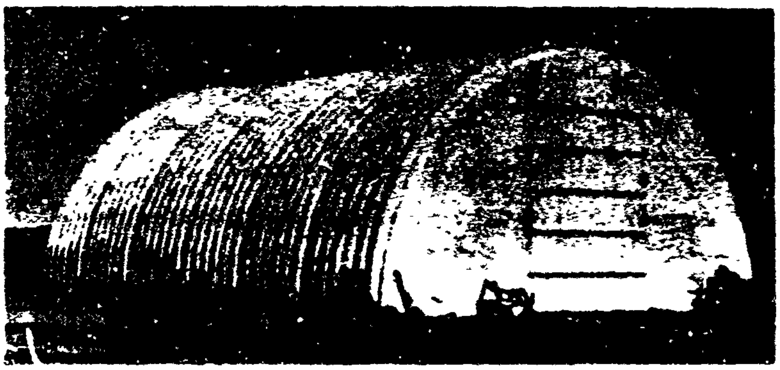

Figure 3. Double-Wall, Cylindrical

Cylinder with flat ends:

$$A_p = W \quad l_h$$

where:

A_p = planform area, sq ft

W = width of tent, ft

l_h = length of tent, ft

The planform areas for tents with radii up to 80 feet are shown in Table I.

The dynamic pressure, q, due to wind velocity is defined by the following expression:

$$q = \frac{\rho U^2}{2}$$

where:

q = dynamic pressure, lb/sq ft
U = wind velocity, ft/sec
ρ = density of air in (slugs/cu ft), $\frac{lb - sec^2}{ft^4}$

= .00238 for a standard day at sea level

The variation of impact pressure with wind speed at sea level and 59°F is shown in Figure 4. An impact pressure correction factor as a function of pressure altitude and temperature is shown in Figure 5.

In single wall shelters, the lift due to internal pressure must be added to the aerodynamic lift. The load on the anchors due to internal pressure can be calculated from the following expression:

$$AL_e = P_e A_f$$

AL_e = anchor load due to internal pressure, lbs

Table I

TENT PLANFORM AREA, A_p

SPHERICAL AND CYLINDRICAL TENTS WITH HEMISPHERICAL ENDS

Tent Radius r Ft.	Tent Planform Area, A_p, Sq. Ft.			
	Spherical	Cylindrical $1/2 = W/l_h$	Cylindrical $1/3 = W/l_h$	Cylindrical $1/4 = W/l_h$
10	314	714	1114	1514
12	452	1028	1604	2180
14	615	1399	2183	2967
16	804	1828	2852	3876
18	1017	2313	3609	4905
20	1256	2856	4456	6056
22	1520	3456	5392	7328
24	1809	4113	6417	8721
26	2123	4827	7531	10235
28	2463	5599	8735	11871
30	2827	6427	10027	13627
32	3216	7312	11409	15505
34	3631	8255	12879	17503
36	4071	9255	14439	19623
38	4536	10312	16088	21864
40	5026	11426	17826	24226
42	5541	12597	19653	26709
44	6082	13826	21570	29314
46	6647	15111	23575	32039
48	7238	16454	25670	34886
50	7853	17854	27854	37854
52	8494	19310	30126	40942
54	9160	20824	32488	44152
56	9852	22396	34940	47484
58	10568	24024	37480	50936
60	11309	25709	40109	54509
62	12076	27452	42828	58204
64	12868	29252	45636	62020
66	13684	31108	48532	65956
68	14526	33022	51518	70014
70	15393	34993	54593	74193
72	16286	37022	57758	78494
74	17203	39107	61011	82915
76	18145	41249	64353	87457
78	19113	43449	67785	92121
80	20106	45706	71306	96906

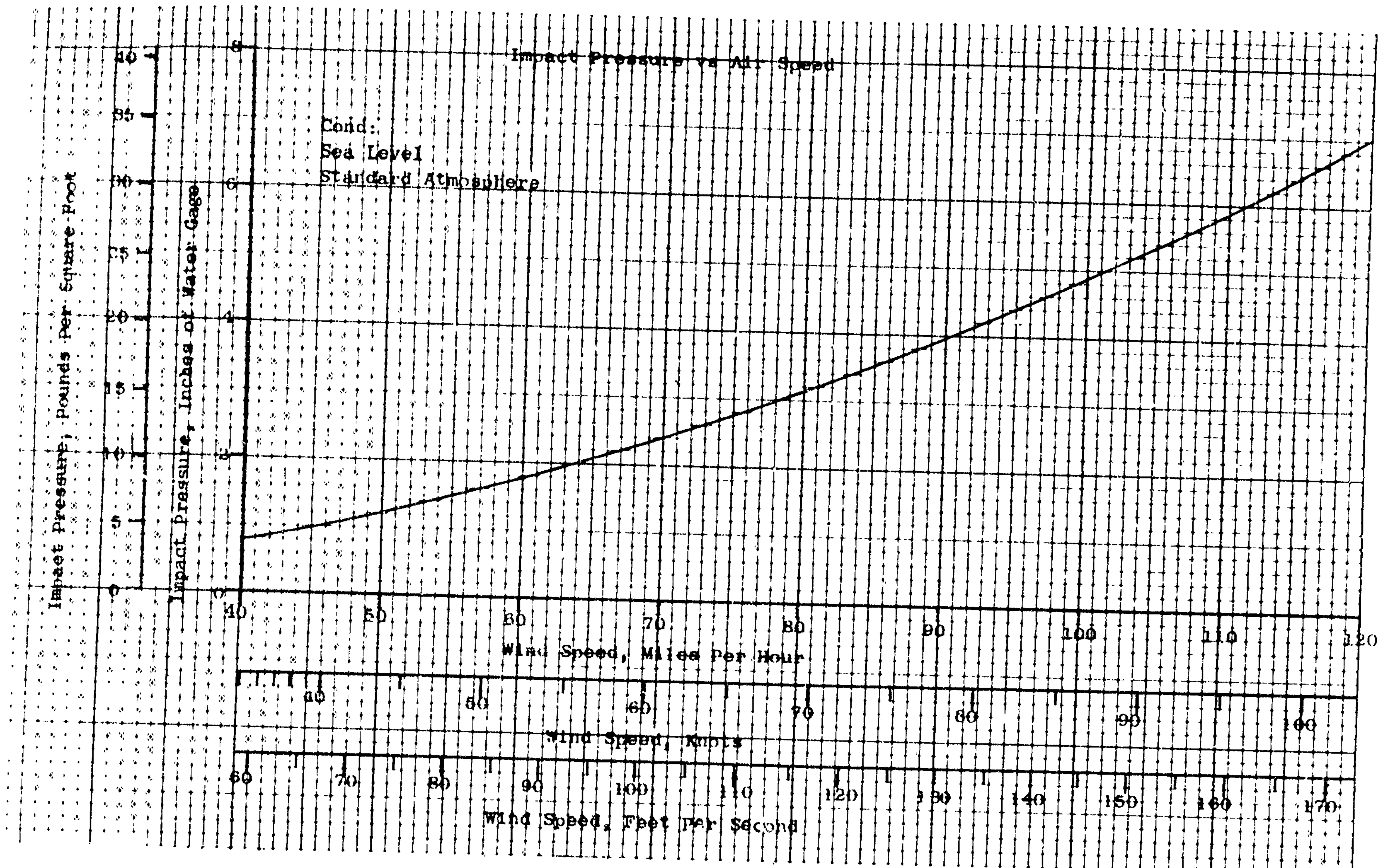

Figure 4. Variation of Impact Pressure with Air Speed, Sea Level Standard Atmosphere

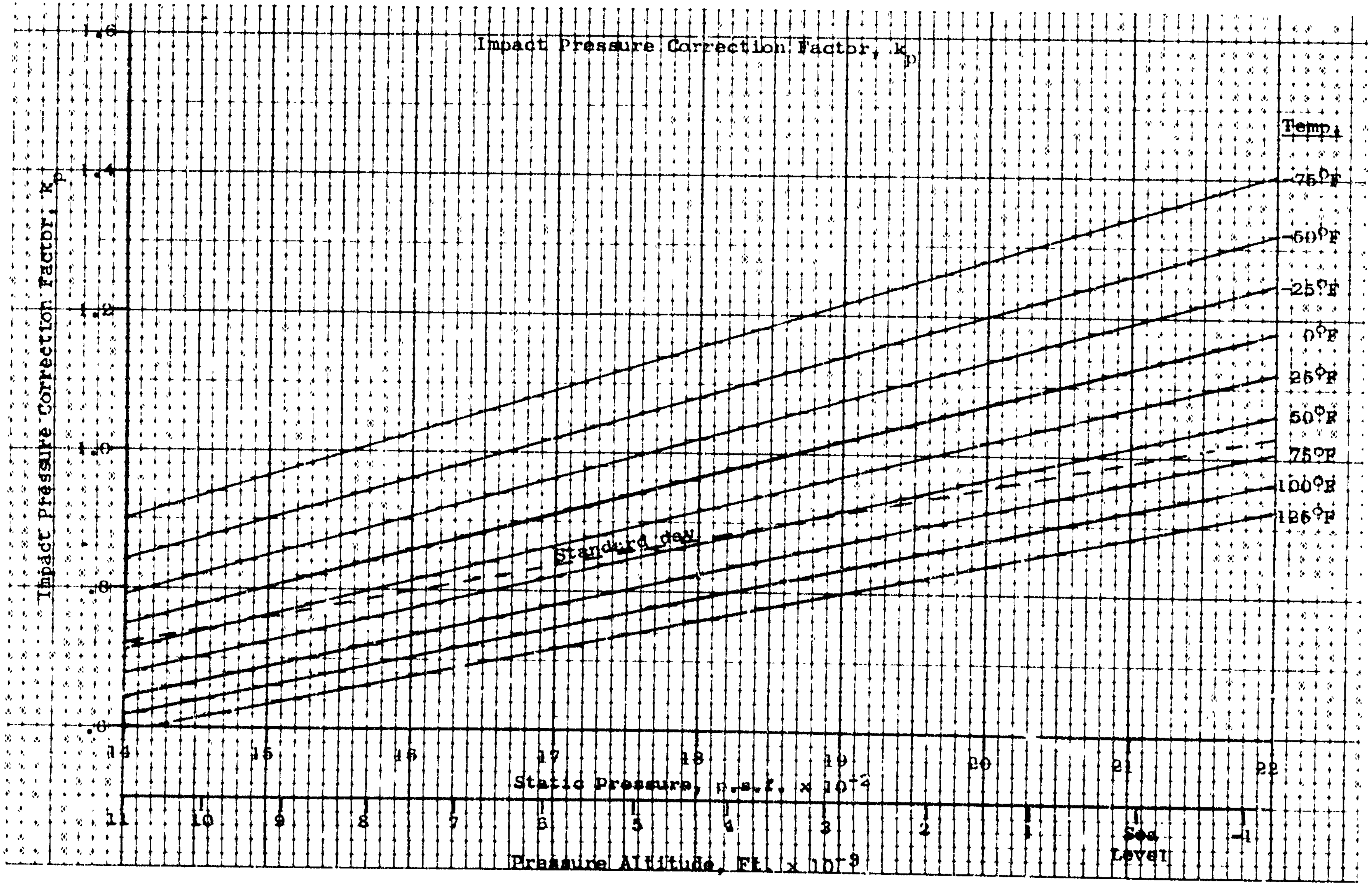

Figure 5. Impact Pressure Correction Factor, k_p, Variation with Altitude and Temperature

P_e = internal pressure, lbs/sq ft

A_f = floor area, sq ft

To summarize, the total force that must be resisted by the shelter anchoring system is created by the:

(1) Aerodynamic load for double wall shelters
(2) Aerodynamic load PLUS internal pressure for single wall shelters.

b. Definition of Anchor Load Coefficients

The general definition of an anchor load coefficient due to aerodynamic forces is:

$$C_{AL} = \frac{AL}{qA_p}$$

where:

AL = anchor load, lbs

C_{AL} = anchor load coefficient

In double wall shelters the anchor load is carried by anchors at the base of the shelter, as well as, by anchors securing the guylines. The coefficients associated with these two loads are:

$$C_{BL} = \frac{BL}{qA_p}$$

$$C_{GL} = \frac{GL}{qA_p}$$

C_{BL} = Anchor load coefficient for base of shelters.

C_{GL} = Anchor load coefficient for guy lines.

BL = Anchor load on base, lbs.

GL = Anchor load on guy lines, lbs.

q = Dynamic (Impact) Pressure lbs/sq ft

Anchor load coefficients as a function of width/length and height/diameter ratios are plotted in Figures 6, 7 and 8.

c. Formulas for Calculating Anchor Loads

Using Figures 6, 7, and 8 it is a simple matter to estimate the maximum anchor load on an air supported structure. The problem resolves itself to geometry and substitution into formulas. The items of information required are:

Shelter geometry
Design wind speed
Enclosure pressure (single wall only)

(1) Single Wall Shelters

Total Anchor Load $P_{AL} = C_{AL} q A_p + P_e A_f$

(2) Double Wall Shelters

$BL = C_{BL} qA_p$

$GL = C_{GL} qA_p$

Total Anchor Load $P_{AL} = qA_p \quad (C_{BL} + C_{GL})$

The way the calculated load is distributed is a matter for the tent designer. If the anchoring system consists of individual anchors equally spaced around the shelter and the holding capability of the anchor is known, the total load divided by the anchor holding power will determine the number of anchors to be used. If the shelter is to be continuously held down along the floor perimeter, the total load divided by the shelter perimeter determines the load/foot.

The U.S. Army uses several types of anchoring systems such as concrete pads with metal hold down bolts. steel hold down rings on towers and arrowhead ground anchors. The arrowhead anchors, as described in MIL-A-3962A, Anchors, Ground, Arrowhead, 4", 6" and 8" with Auxiliary Equipment, are generally used for field installations. Considerable work is being done by the Natick Laboratories to determine the holding capabilities of the 4" arrowhead anchor in various types of soil. This work will be reported separately after it is completed. To give an indication of the order of magnitude of the holding power, 4" anchors, when driven to their full depth of 28" will hold about a 1000 lbs in sand and about 2000 lbs in sandy gravel.

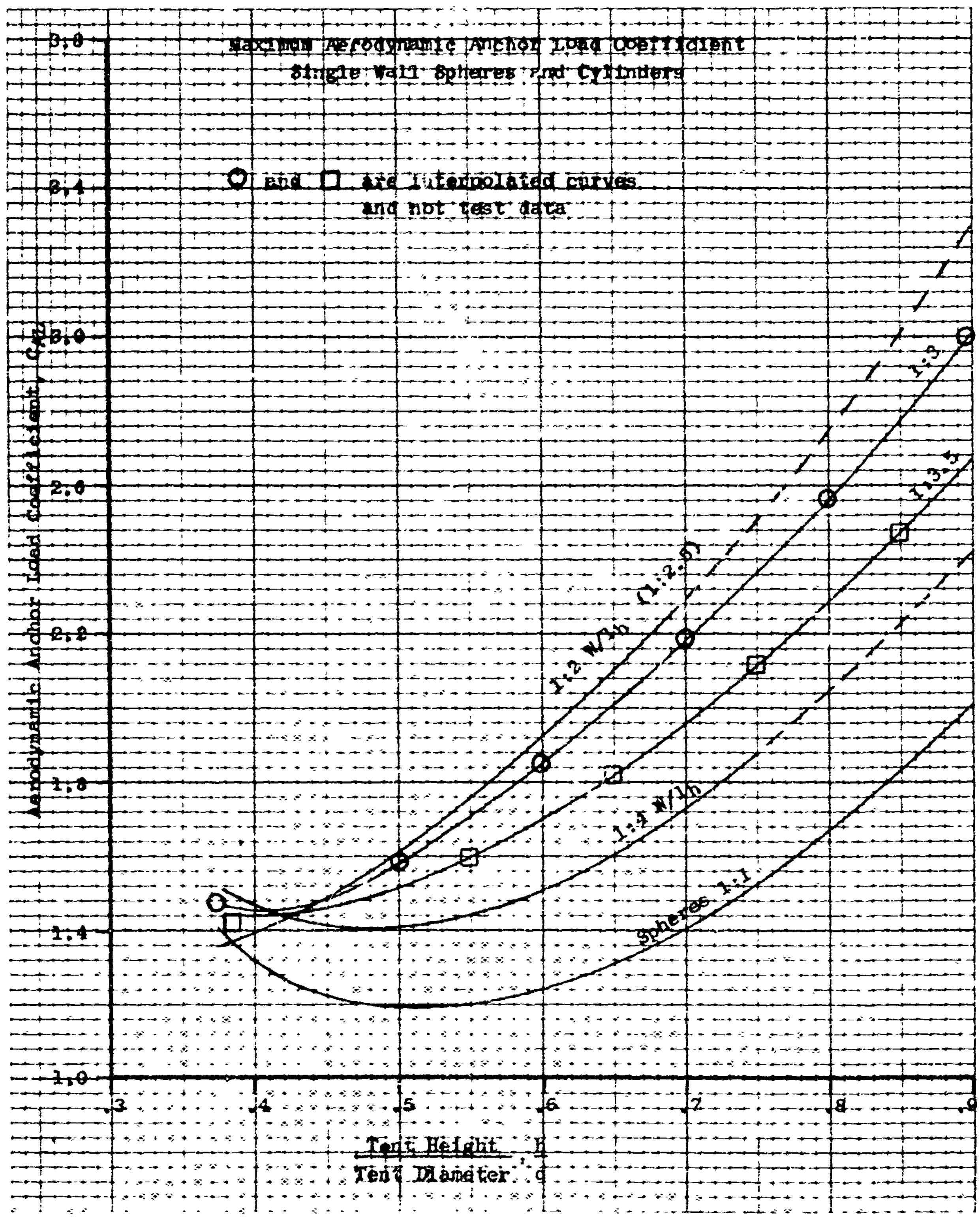

Figure 6. Variation of Anchor Load Coefficient with Shape

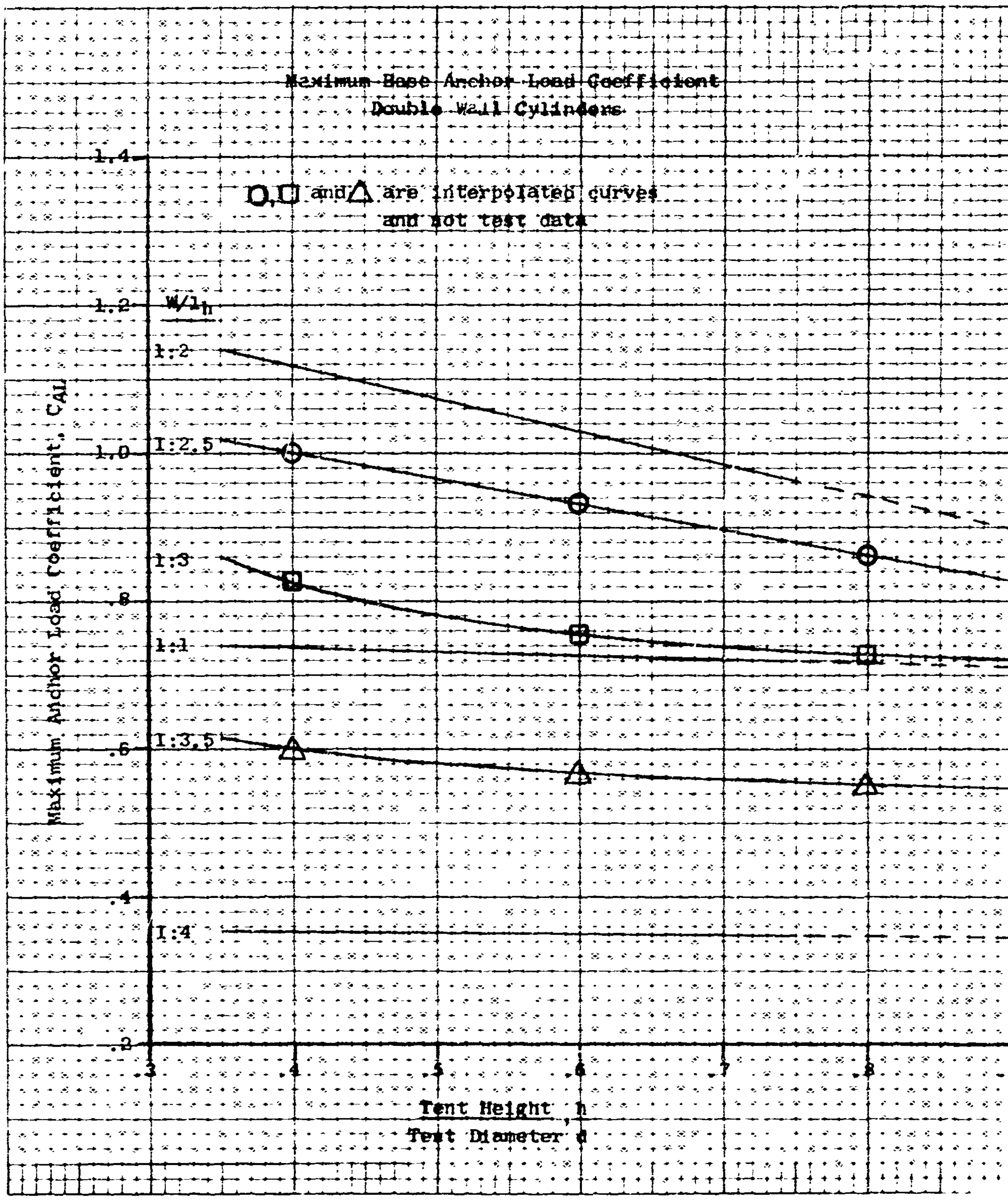

Figure 7. Variation of Base Anchor Load Coefficient-Shape

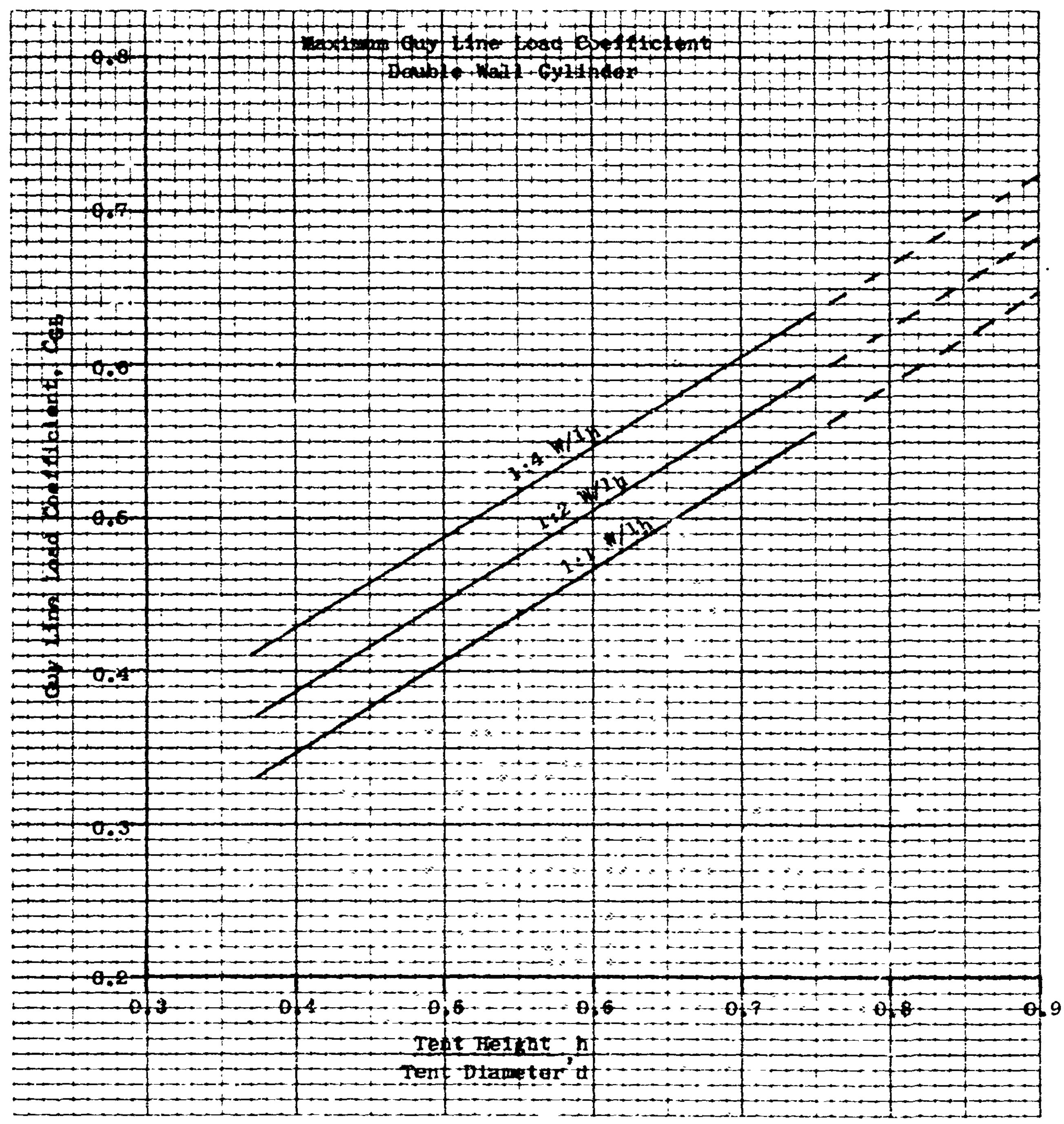

Figure 8. Variation of Guy Line Load Coefficient with Shape

Anotner fact of interest is that for anchors driven 28-30" the minimum distance between anchors should be at least 30 inches. These figures are presented for illustrative purposes only and will indicate the type of information required concerning the anchoring system to be used on the shelter being considered.

d. Sample Calculations

(1) The following calculations are for the single-wall, spherical shape (Fig. 9):

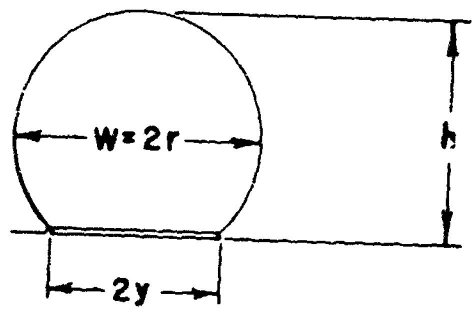

Figure 9. Single-Wall Sphere

Width = W = 30 ft = 2r
Height = h = 22.5 = ft
Sea level
Temperature expected + 60 to -30°F
Wind velocity = 90 knots
Enclosure pressure = q

Geometric Considerations

Length of chord = $2y = 2\sqrt{r^2 - (h-r)^2}$

$$y = \sqrt{2hr - h^2}$$

$$y^2 = 2(22.5)(15) - (22.5)^2 = 169$$

$$y = 13 \text{ ft}$$

$$A_f = \pi y^2 = 169\pi = 531 \text{ sq ft}$$

$$\text{Perimeter} = 2\pi y = 2\pi(13) = 82 \text{ ft}$$

$$A_p = \pi r^2 = \pi (15)^2 = 709 \text{ sq ft}$$

Determining impact pressure, q

Figure 4 - at 90 knots, q (standard) = 27 psf (lb/sq ft)

Figure 5 - max correction factor = 1.21

Actual q = 1.21 (27) = 32.7 psf

Anchor loads

Aerodynamic load

$h/d = 22.5/30 = .75$

$w/l_h = 30/30 = 1.0$ (sphere)

Figure 6 - $C_{AL} = 1.5$

Wind load = $C_{AL}\ qA_p = 1.5\ (32.7)\ (709)$

$= 34{,}700$ lbs

Inflation pressure load = $P_e\ A_f$

$= (32.7)\ (531)$

$= 17400$ lb

Total Load = 34700 + 17400 = 52,100 lb

Distributing Anchor Load

Assume an anchor holds 1500 lb

No. of anchors $\dfrac{52100}{1500} = 35$

Anchor spacing $\dfrac{82}{35} = 2.34$ ft

(2) The following calculations are for the single-wall, cylindrical shape with spherical ends (Fig. 10):

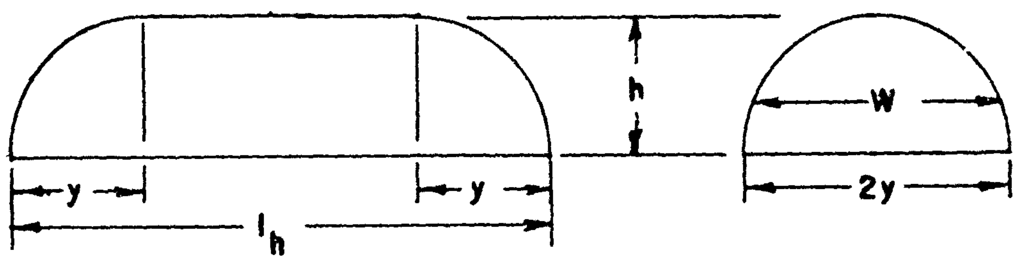

Figure 10. Single-Wall Cylinder

Width = W = 50 ft = 2r
Height = h = 25 ft
Length = l_h = 100 ft

Sea level standard atmosphere
Wind velocity - 105 mph
Enclosure pressure = q

<u>Geometric considerations</u>

Length of Chord $2y = 2\sqrt{r^2 - (h-r)^2}$

$$y^2 = 2hr - h^2$$

$$y^2 = 2(25)(25) - (25)^2 = 625$$

$$y = 25 \text{ ft}$$

$$A_f = \pi y^2 + 2y(l_h - 2r)$$

$$= 625\pi + 50 (100-50)$$

$$A_f = 1962 + 2500 = 4462 \text{ sq ft}$$

Perimeter = $50\pi - 100 = 256$ ft

$$A_p = \pi r^2 + 2r(l_h - 2r)$$

$$= 625\pi - 50(100-50) = 4462 \text{ sq ft}$$

In this example the planform area equals the floor area which is not always the case.

Determining impact pressure, q

Figure 4 at 105 mph, q = 28 psf

Anchor loads

Aerodynamic load

$h/d = 25/50 = .5$

$W/l_h = 50/100 = .5$

Figure 6 $C_{AL} = 1.6$

Wind load = $C_{AL}\, qA_p = 1.6\ (28)\ (4462)$

$= 200{,}000$ lbs

Inflation pressure load = $P_e\, A_f$

$= 28\ (4462)$

$= 125{,}000$ lbs

Total Load = $200{,}000 + 125{,}000 = 325{,}000$ lbs

Distributing Anchor Load

Assume an anchor holds 2000 lbs

No. of anchors $\frac{325{,}000}{2000} = 163$ anchors

Anchor spacing $= \frac{256}{163} = 1.57$ ft.

This spacing is quite close for a 4" arrowhead anchor system but might be suitable or other types. If arrowheads are needed, larger anchors, deeper emplacement or pairs of 4" anchors could be used to increase spacing.

(3) The following calculations are for the double-wall, cylindrical shape with flat ends (Fig. 11):

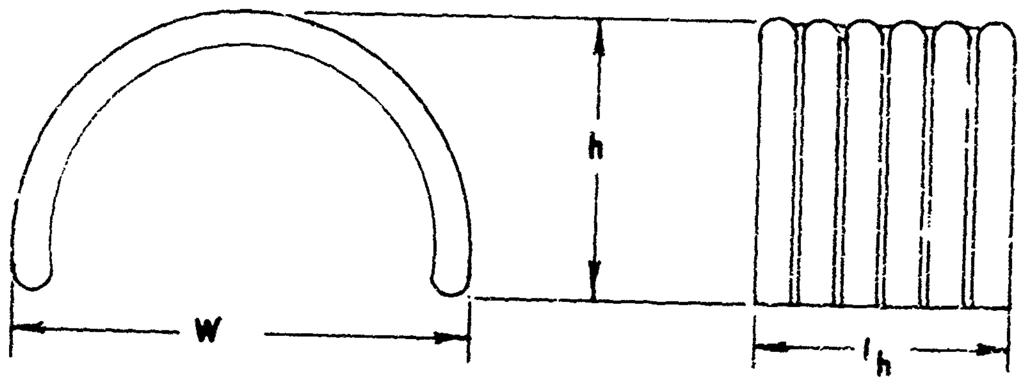

Figure 11. D-W Cylinder

Width = W = 100 ft
Height = h = 50 ft

Length = l_h = 200 ft
Sea level, standard atmosphere
Wind velocity -105 mph

Geometric considerations

Length of anchored sides 2(200) = 400 ft

A_p = W/h

= 100 (200) = 20000 sq ft

Determining impact pressure, q

Figure 4 at 105 mph q = 28 psf

Anchor loads

h/d = 50/100 = .5

W/l_h = 100/200 = .5

Figure 7, C_{BL} = 1.08

Figure 8, C_{GL} = .44

Total Anchor Load $P_{AL} + qA_p (C_{BL} + C_{GL})$

$P_{AL} = 28 (20000) (1.08 + .44)$

$= 856000$ lbs

$BL = 1.08 (28) 20,000 = 607,000$ lbs

$GL = .44 (28) 20,000 = 249,000$ lbs

Two points to be noted are the extreme forces possible on an air-supported structure and the fact that the base of the shelter requires three times as much anchoring as the guylines. The latter factor is contrary to common belief but has been indicated consistently in the wind tunnel studies performed on model double-wall shelters.

Distributing Anchor Loads

Assume an anchor holds 4000 lbs

No. of Base Anchors $\frac{607000}{4000} = 152$

No. of Guyline Anchors $\frac{249000}{4000} = 62$

Spacing along base $\frac{400}{152} = 2.63$ ft

Spacing of guyline $\frac{400}{62} = 6.5$ ft

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